Redshift Range Strategy for SNAP

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Abstract

Observations out to $z \approx 1.5 - 2$ are required to discriminate between dark energy models, whether between cosmological constant, constant w tracking models, or evolving quintessence models. Given the current expected equation of state range of $-1 \lesssim w \lesssim -0.6$, constrained by observation and theory, experiments with an accuracy worse than $\delta w = 0.1$ (68% confidence) will add little to our knowledge of dark energy and field theory. Probing the cosmology to $z \approx 1.5 - 2$ with supernovae can provide better than this accuracy, along with sensitivity to time variation, complementarity, and protection against systematic effects such as grey dust.

1 Cosmological Parameters: Degeneracy and Confusion

At an initial theoretical glance, it is simple to understand the redshift range over which dark energy is most easily probed. The Friedmann equations trace the expansion rate and the acceleration in terms of the energy density parameters and the equations of state (EOS) of the components. These define epochs of transition between matter and dark energy density dominance z_{eq} and transition between decelerating and accelerating expansion z_{ac}.

As seen in Fig. 1, most of the action in either changeover of the dynamics happens at fairly low redshifts, $z \approx 0.5$. This is in marked contrast to distinguishing between cosmological models with fixed EOS, say between models with different matter density, where the expansion behavior diverges at high redshifts. But it is too narrow a view to say that this implies that

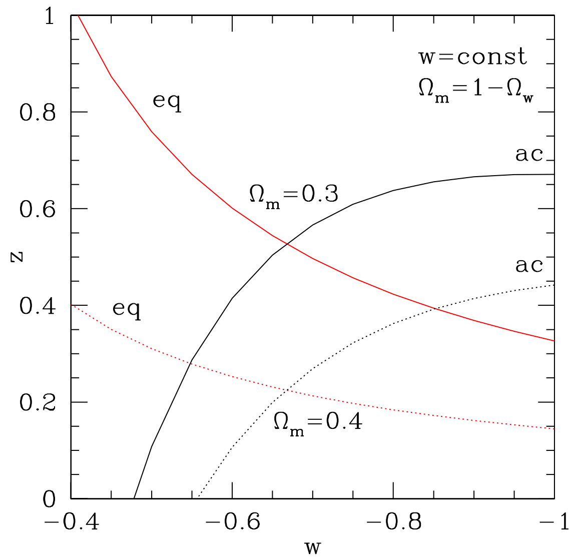

Figure 1: Transition epochs of matter–dark energy density equality and decelerating to accelerating expansion are plotted vs. equation of state of the dark energy, for a flat universe. Solid curves have $\Omega_m = 0.3$, dotted have $\Omega_m = 0.4$.

detection of the main influence of a dark energy component requires probing the expansion history to only this modest redshift.

Low redshift measurements could provide evidence for the existence of dark energy but not the distinctions required to minimally characterize its properties: is its EOS detectably different from the cosmological constant and does it vary with time.

Note that observations from supernovae in combination with other methods already indicate that the equation of state of the dark energy is $w \leq -0.6$ at the 95% confidence level. Thus a measurement with an uncertainty of $\sigma_w = 0.2$ will tell us nothing new, and even experiments with $\sigma_w = 0.1$ are of limited use since the estimated w could lie in the middle of the allowed range, e.g. $w = -0.8 \pm 0.1$ (1σ) again does not allow us to clear up or even narrow the present uncertainty between a cosmological constant $(w = -1)$ and a dynamical scalar field. Note for example that the projected precision from the Planck cosmic microwave background experiment is $\sigma_w = 0.25$, for a weighted average between the present and $z = 1100$, with no power to discern time variation.

Without a long redshift baseline, measurement results beyond the expected EOS borderlines, e.g. $w = -1.2$, would not tell us whether there existed even more exotic physics (e.g. nonlinear scalar fields that possess $w < -1$) or unappreciated systematics (e.g. reddening of supernovae due to undetected dust). Furthermore, there exist a plethora of high energy physics inspired models that lie close to $w = -1$ at the present. Mere estimation or even moderately precise determination of w is insufficient. Detection of, or limits on, time variation of the equation of state by observations over a broad redshift range $z = 0 - 1.5$ is the one key piece of evidence to guide us in future models of the fundamental physics responsible for dark energy.

Thus naive estimates of measurement accuracy and redshift range à la Fig. 1 fail, even as to distinguishing broad classes of dark energy models. The physical reasons for this include the nonlinear evolution of the effective EOS w_T of the total energy density (currently more negative components fade more quickly into the past and are surpassed by less negative ones) and the nonlocal relation between the EOS and the supernova magnitude or distance (models with the same $w_T \equiv \rho_{\rm total}/p_{\rm total}$ at some z need not have the same magnitude there). That is, even when the dynamical impact of the dark energy fades, the integral nature of the distance-redshift relation preserves some of its influence.

Figure 2 illustrates these effects. The bottom half plots the total EOS showing the increased dilution of the dark energy due to increasing matter domination. The nonlinearity is evident as the ordering of curves from more negative to less negative dark energy EOS inverts from low to high redshift. The top half plots the magnitude difference from the $w = -0.7$ model and clearly show the nonlocality. At $z \approx 0.8$, where the total EOS of each constant w model agree, there is still a nonzero and increasing separation in the Hubble diagram. Even at high redshifts where the dark energy is dominated by the matter and the w_T approach zero, there is an inertia effect leading to a persistence of dark energy influence.

To achieve characterization allowing discrimination *between* dark energy models to better than $\delta w_0 = 0.1$ and $\delta w_1 = \delta(dw/dz) = 0.2$ requires a survey depth of $z \gtrsim 1.5$ with distance measurements to 1% (in terms of magnitudes $\delta m = 0.02$), including both statistical and systematic errors. Uncertainties in w_0, w_1 increase roughly linearly with poorer δm.

The "confusion limit" of this criterion is shown, in Fig. 3, with a cau-

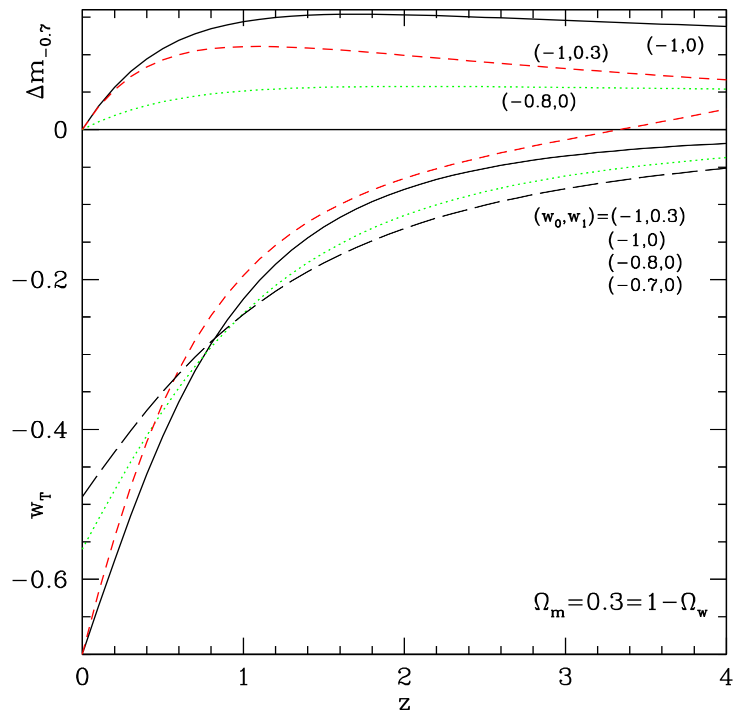

Figure 2: The bottom half of the plot shows the total equation of state w_T of the dark energy plus matter as a function of redshift z for three constant w models and one model evolving as $w(z) = w_0 + w_1 z$, labeled from top to bottom at high redshift. The curves cross as more negative EOS models are diluted more rapidly by the matter component. The top half gives the differential magnitude-redshift relation for the same models, with respect to the $w = -0.7$ model. Characteristics include divergence even beyond z_{eq} and slow turnover due to inertia, providing an extended redshift baseline for detecting dark energy.

tionary note. Although all the models graphed have their "action" redshifts z_{eq} and z_{ac} at $z < 0.7$, observations extending only to $z = 0.7$ are clearly insufficient to probe the cosmological model. One could not tell whether one is dealing with a constant equation of state different from a cosmological constant, a rapidly evolving dark energy model, or a purely cosmological constant model at a slightly different energy density.

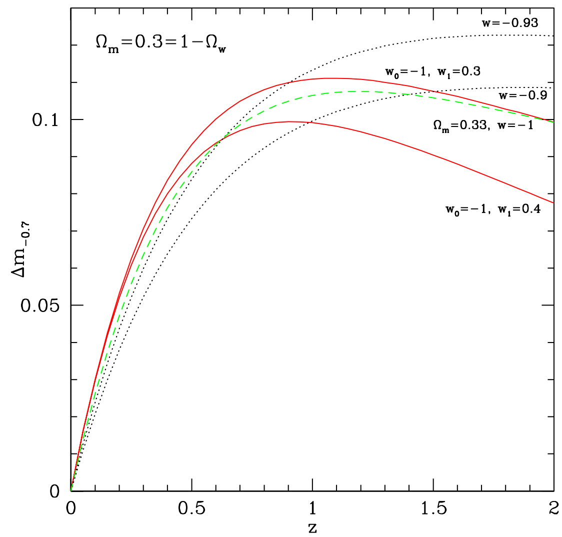

Figure 3: Magnitude-redshift relations relative to the constant model $w = -0.7$ are plotted for flat, linearly evolving dark energy models $w = w_0 + w_1 z$. Prospective SNAP (Supernova/Acceleration Probe) error bars of 0.02 in magnitude will be able to distinguish between constant and evolving dark energy and also between sufficiently different evolution behaviors by observing in redshift out to $z = 1.7$.

Surveys extending out to $z \approx 1.5 - 2$ can make such distinctions, even down to fairly fine differences (the curves were chosen to represent roughly those "confusion limits"). One caution however is that complementary constraints, e.g. on the matter energy density Ω_m, total energy density Ω_T, or the absolute supernova magnitude $\mathcal{M}$, from other cosmological probes or low redshift supernovae data play a crucial role in limiting the parameter space of dark energy models.

This confusion criterion places much more stringent constraints on the redshift depth than the parameter degeneracy breaking requirement (e.g. separating a combination of Ω_m and Ω_w, which can be easily satisfied by low redshift complementary probes) or the physical dynamics of the dark energy (through z_{eq} or z_{ac}). Plus as we saw in Fig. 2, signs of dark energy do not quickly fade away for $z > 0.7$; an extended redshift baseline is both required and advantageous. In the next section we consider further redshift range requirements due to noncosmological factors, including astrophysical systematics and field theory dynamics.

2 Astrophysics and Field Theory: Systematics and Time Variation

The squeeze play between the low redshift convergence of all tests to linear Hubble flow behavior and the higher redshift dynamical insignificance of dark energy leaves a region from $z \approx 0.2-2$ accessible for cosmological probes. The best ones cover most of this range. However this then leads directly to the critical issue of systematics: understanding the physical systems used in the experiment over a lookback time extending for 70% of the age of the universe. This must be done well enough to give confidence in interpretation of the results in terms of cosmological parameter values rather than astrophysical variation and evolution.

These include issues such as the structure, evolution, and nongaussianity of clusters and galaxies in number tests, nonlinear mass distribution and evolution in weak lensing, and selection effects and gas dynamical processes in the SZ effect. Plus, while many of these tests have good statistical sensitivity to the value of w, they do not probe its time variation – the "smoking gun" distinction from a cosmological constant, especially if w is near -1, and a key window on the type of high energy field theory responsible for the dark energy.

Complementary probes do play a critical role in constraining the parameter space, e.g. Ω_m, lifting degeneracies, and independent confirmation. They can provide initial indications of the value of the dark energy equation of state, though not to any real extent its time variation, subject to problematic systematic error estimates. But this role, though necessary, is insufficient. As Steven Weinberg points out in his *Research Book* contribution, "it is difficult for physicists to attack this [vacuum energy] problem without knowing just what it is that needs to be explained."

The supernovae Hubble diagram method has the advantage of already identified sources of systematics, including possible progenitor and environment dependence, with a third generation experiment such as SNAP well suited to addressing them (indeed SNAP is considerably less a "new" experiment than any of the alternatives, plus it also provides an independent probe in its weak lensing survey). Two further assets are that the very nature of supernovae spectra is a rich stream of data probing progenitor characteristics and evolution, with cross checks between different light curve epochs and different supernovae, and that the underlying simple physics of supernovae is not expected to evolve in the cosmological sense. That is, Type Ia supernovae do not depend on cosmic time, only their local conditions – this is the only "evolution" they know. With plentiful data we could compare like to like from high to low redshift and control luminosity standardization to high accuracy.

So a large range in redshift does no harm with respect to our understanding of the supernovae method, but does have benefits for our knowledge of cosmological parameters even beyond the increased baseline of the expansion history. A secular deviation such as the dimming effects of grey dust will show up most strongly when observed to appreciable redshift. Subtraction of this systematic is crucial to determining the correct class of high energy physics theories through the dark energy EOS since such dust causes us to underestimate w, driving it more negative. We could misconstrue a dynamical scalar field with $w=-0.8$ as a $w=-1$ cosmological constant, or be faced with the dilemma of not knowing whether a measurement of $w=-1.2$ represents an uncorrected systematic or a sign of a nonlinear scalar field with w truly less than -1.

Thus we will not know what theoretical direction to pursue, especially given our ignorance of hypothetical dust properties, unless we extend far enough in redshift to observe nonmonotonic behavior in the (differential) magnitude-redshift relation. Dust reddening can act only to dim supernovae while a turnover in measured magnitudes versus an empty (nonaccelerating) universe is the signal of transition from accelerating to decelerating expansion.

[Note that while gravitational lensing drives w to less negative values, it is a much smaller effect, giving a dispersion $\delta m \lesssim 0.1$, and can be reduced statistically through large numbers of supernovae in a redshift bin.]

Three key characteristics suffice to separate dynamical dark energy models from a cosmological constant vacuum energy: a value of EOS $w \neq -1$, a time variation dw/dz, or inhomogeneity in the dark energy scalar field ϕ. The first is easiest to determine observationally, and what we have discussed measuring in the earlier part of this paper. It requires reducing statistical and systematic errors below $\delta w \approx 0.1$ to improve meaningfully our knowledge and is most realistically achieved by observations extending to $z > 1$. Moreover, models do exist with w very close to -1 at the present, so it is not necessarily a definitive test.

The third sign, spatial variation in the field, is expected to be extremely difficult to detect because of its small magnitude. Presumably fluctuations enter the horizon with amplitude 10^{-5} as follows from inflation and CMB constraints. But they would only grow once the universe becomes dark energy dominated, which is too recent for appreciable growth. Furthermore, since the scalar field has an effective Jeans mass given by $d^2V/d\phi^2$, of order 10^{-33} eV, corresponding to the Hubble scale, inhomogeneity should only be observed at longer wavelengths. Even the most ambitious projects currently planned are unlikely to detect this.

The second property, time variation, would be a clear signal of a dynamical field and provides as well a window on the specific field theory in that dw/dz is directly related to the structure of the field potential $d\ln V/d\ln(1+z)$. Though again models exist that over some limited redshift range exhibit a nearly constant EOS, generically time variation is the key signal of a dynamical field (almost by definition!).

While it would be marvelous to compare the measurement of w today with that at $z = 1100$, say, the CMB does not measure the same quantity as lower redshift measurements. Rather it feels a single density weighted average of the EOS over the entire time back to the last scattering epoch, without sensitivity to the time variations as such. Distance probes to a distributed set of objects, e.g. supernovae or cluster counts at a variety of redshifts, ameliorate this sort of integral problem, and a true differential measurement – so called cosmic tomography – of cosmological conditions within a narrow redshift bin would greatly alleviate it (if statistical and systematic effects could be overcome). While combining experimental methods is extremely useful for cross checks and tightening constraints, it is unlikely to suffice as evidence of time variation per se.

Apart from the gross sense of comparing some $\langle w \rangle$ at different times, the time variation $w_1 = dw/dz$ is more difficult to measure precisely and even more sensitive to spoofing by systematics. For example in a Hubble diagram with a SNAP distribution of supernovae out to $z = 1.7$ and a total magnitude error restricted to $\delta m = 0.02$, the best case determination of $w_0 \equiv w(z = 0)$ is 0.02 (0.08 if $w_1 \neq 0$) but w_1 to 0.19. Larger magnitude uncertainties would blur w_0 and obfuscate w_1 beyond usefulness.

3 Conclusion

Figure 4 illustrates the statistical effect of varying the redshift baseline on determining the dark energy model in terms of its present equation of state w_0 and time variation $w_1 = dw/dz$. In addition there will be important benefits with increasing redshift range in reducing systematics unrelated to the cosmological parameters.

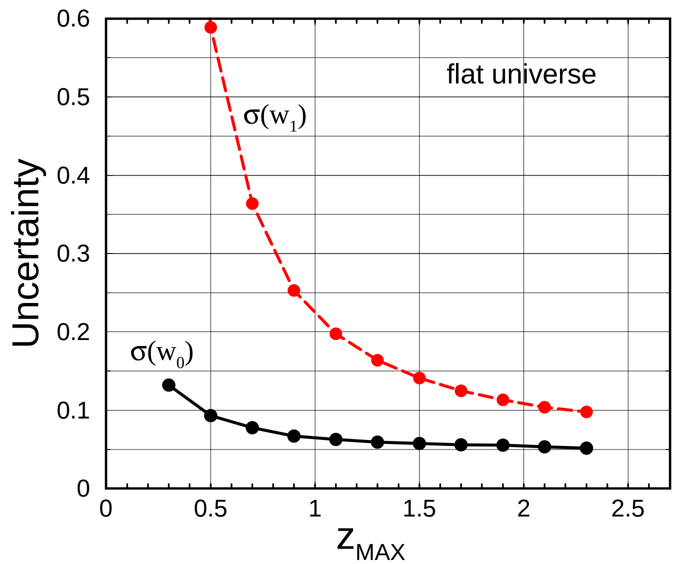

Figure 4: Precision in cosmological parameter determination is plotted as a function of maximum redshift probed in a SN Ia survey. Despite the dark energy becoming dynamically unimportant for $z > 0.6$, a longer baseline experiment continues to make important gains in precision. An increased range should result in needed improvements to systematics as well; only statistical errors are included in the curves.

Our goal should be sufficient progress in the observations to guide us with confidence for the next step in our knowledge of physics and the universe. As Sean Carroll writes in his *Resource Book* article:

> On the observational side, we will either verify to high precision the existence of a truly constant vacuum energy representing a new fundamental constant of nature and a potentially crucial clue

> to the reconciliation of gravity with quantum field theory, or we will detect variations in the dark energy density which indicate either a new dynamical component or an alteration of general relativity itself.

To accomplish this we need to probe to moderate redshifts.

Could we detect dark energy with measurements at $z < 1$? Assuredly – we already have through the supernova method. Could we reliably distinguish its equation of state from that of a cosmological constant? Possibly – large scale ground based surveys possibly together with HST could well give indications of this, though maybe not definitive ones. Could we see the critical evidence of time variation in the equation of state that would set fundamental physics into a ferment of activity and exploration? No. For that we require detailed observations out to $z \approx 1.5 - 2$ and control of systematics. The science goals and methods are clear; the prize is a deep look into the nature of physics and the fate of the universe.